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EXTRA-SOLAR PLANETARY SYSTEMS

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RESUMEN

Se hace una breve reseña de hechos relacionados al descubrimiento de varios sistemas multi–planetarios alrededor de estrellas cercanas y la estabilidad de los sistemas bajo la presencia de resonancias. Se muestra el dominio del movimiento caótico cerca de un planeta del sistema PSR 1257+12

ABSTRACT

We present a short account of facts related to the discovery of several multiplanet systems around nearby stars, and of the systems stability in presence of resonances. The domains of chaotic motion near one planet of PSR 1257+12 are shown.

Key Words: **PLANETARY SYSTEMS, CELESTIAL MECHANICS**

1. INTRODUCTION

The more recent lists show 70 new planets around nearby stars, almost all of them discovered by means of spectroscopic measurements of the stars radial velocities, in the past 6 years. The discovery technique explains the biases of the current sample. In a single planet system, both star and planet move themselves in ellipses around a common center of gravity. The two motions are identical but the star moves on an ellipse much smaller than that of the planet. For instance, in the Sun-Jupiter system, the speed of Jupiter in its orbit is 13 km s^{-1}, but the speed of the Sun is $\sim 10^3$ times smaller, that is, 13 m s^{-1}. The spectrum seen by the observers, comes from the star, not from the planet. Therefore, what the observer would measure in the case of a Sun-Jupiter like system would be a $\sim$ 12-yr variation with a $\sim$ 13 m s^{-1} semi-amplitude. Thus, to detect the existence of one Jupiter-like planet around a Sun-like star, one observer should be able to measure radial velocities with a precision better than 13 m s^{-1}. This possibility is very recent and only a few instruments allow measurements better than 10–20 m s^{-1} to be done.

These details are important to understand the sample we have: large planets, with masses from a few tenths to ten Jupiter masses, in orbits close to the central star. The closeness to the central star acts in two ways: first, the speed of one planet – and its counterpart in the motion of the star– are inversely proportional to the square root of the star-planet distance; second, the period of the motion is inversely proportional to the cube of the speed. A large planet at a small distance from the star has a higher radial-velocity variation and a shorter period, thus increasing its chances of being discovered. It is not wonder that the sample we have is so biased: most of the discovered exoplanets are big and lie very close to the star. Even if these discoveries are bringing us a great deal of new knowledge, we shall be aware that the sample we have is biased and does not allow taxonomic studies to be done. Another difficulty related with the observational techniques is that the observed velocity is a projection of the actual velocity on the line of sight, thus creating an indetermination. We cannot determine the masses of the planets, but only the product $M.\sin i$ where i is the inclination of the planet orbital plane to a plane normal to the line of sight.

The continued observation of the discovered planets and the increasing accuracy are starting to show that many discovered planets are not alone around their stars: they are accompanied of other planets and, at this moment, 8 planetary systems with 2 or 3 planets are known around main sequence stars (see Table 1 taken from Schneider, 2001)

Before discussing the data given in Table 1, let us add that one of the discovered extra-solar planetary system lies not around a main sequence star, but around one pulsar. In fact, the discovery of this system happened long before the others. It was not discovered by radial velocity measurements (the central star is not even visible), but from variations in the time of arrival of the pulsar pulses. The detec-

TABLE 1

Extrasolar Planetary Systems

Star (type)	$M.\sin i$ ($M_{\rm Jup}$)	Semi-axis (AU)	Period (days)	Eccent-ricity
HD 83443	0.35	0.038	2.9861	0.08
(K0 V)	0.16	0.174	29.83	0.42
υ And	0.71	0.059	4.6170	0.034
(F8 V)	2.11	0.83	241.2	0.18
	4.61	2.50	1266.6	0.41
55 Cnc	0.84	0.11	14.648	0.051
(G8 V)	>5	>4	(> 8 yrs)	?
HD 74156	1.56	0.276	51.61	0.649
(G0)	>7.5	4.47	$\sim$ 2300	0.395
Gliese 876	1.98	0.21	61.02	0.27
(M4 V)	0.56	0.13	30.1	0.12
47 Uma	2.54	2.09	1089	0.061
(G1 V)	0.76	3.73	2594	<0.2
HD 82943	0.88	0.73	221.6	0.54
(G0)	1.63	1.16	444.6	0.41
HD 168443	7.2	0.29	57.9	0.54
(G5)	17.1	2.87	$\sim$ 2140	0.2
B 1257+12	0.015[a]	0.19	25.34	0
(PSR)	3.4[a]	0.36	66.54	0.0182
	2.8[a]	0.47	98.22	0.0264

[a]Earth masses

tion principle is the same described above. When the star, in motion around the system center of gravity, moves towards the Earth, the time between two consecutive pulses is shorter than when it is moving in the opposite direction. As pulse timings are done with a very high precision, they have allowed the detection of Earth-size planets: two of the planets of the pulsar B 1287+12 have about 3 Earth masses and the third one is only larger than our Moon.

2. ORBIT DETERMINATION

Dynamically, a star-planet system is not different from a binary star and all techniques used for a long time to determine the orbits of single-line spectroscopic binaries were translated to planetary systems. However, limitations soon appeared. First were the problems related to the motion of the observer: the radial velocity measured by an observer is the rate of variation of the distance star-observer. Thus, not only the movement of the star is being measured, but also the motion of the Earth. For the analysis of the radial velocities of spectroscopic binaries, which may reach up to some hundred km s^{-1}, it was enough to consider the velocity of the observer as formed by three components: (1) a constant velocity $V_E = 29.76$ km s^{-1}, perpendicular to the radius vector, due to the annual motion of the Earth around the Sun; (2) a correction $eV_E = 0.47$ km s^{-1}, perpendicular to the major axis, due to the ellipticity e of Earth's orbit; (3) the diurnal rotation of the Earth (0.46 km s^{-1} at the equator). This picture is clearly insufficient when dealing with measurements whose precision is around 10 m s^{-1}. For instance, the velocity of the Sun in a frame fixed at the center of gravity of the Solar System, due to Jupiter, and the velocity of the Earth around the center of gravity of the Earth-Moon system are close to 13 m s^{-1}. In the case of timings of pulsar pulses, the situation is still much more stringent: it is not only necessary to use a complete model of the Solar System (as the model adopted in JPL ephemeris), including the Moon, but also several relativistic corrections (Chandler 1996). The incorrect handling of these corrections may lead to interpret as a new planet, variations due to dynamical or physical phenomena in our neighborhood. Good quality ephemeris exists and allows observers to correctly take into account the motion of the Earth in the reduction of spectroscopic observations. However, to get rid of physical effects related to motions in the photosphere of the star – which are of order of 10 m s^{-1}– or of the interactions of radio waves with the solar wind, is much more difficult and we can not exclude that they come to explain some of the observed variations.

In general, the discoveries of planets in a system are not done at the same time. First, the planet responsible for the largest variations is discovered and a Keplerian orbit determined. Then, as the observations continue being done, the observed radial velocities are compared to those expected from a single planet effect. The existence of a second planet does not allow a good agreement to be obtained, residuals appear, which, later, serve to determine a Keplerian orbit for the second planet. However, this hierarchical procedure of determining two Keplerian orbits may lead to problems. For instance, in the case of the three planets of υ And, we do not know which is the frame of the orbits thus determined and different hypotheses on it may transform this system from stable to unstable. The best guess is that they are orbits in Jacobian coordinates, that is, the orbit of the first planet is referred to the star, that of the second planet is referred to the baricenter of the system formed by the star and the first planet,

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and so on. (Laughlin & Adams 1999; Rivera & Lissauer 2000; Rivera & Lissauer 2001; Stepinski et al. 2000). The truth is that the techniques for the Keplerian orbit determination of spectroscopic binaries can only be used for single exoplanets. When we have two massive planets, the orbits can no longer be considered as Keplerian and the radial velocity curve cannot be analyzed with techniques developed to account for single Keplerian orbits. The most notorious example is the planetary system of Gliese 876 (Marcy et al. 2001) whose planets have masses $\sim$0.004 and $\sim$0.01 of the star mass and show radial velocity variations with amplitudes 85 and 200 m s^{-1}, respectively. The interaction between the two planets produces perturbations in their motion that, in 5 years may lead to differences larger than 50 m s^{-1}(Laughlin & Chambers 2001).

If mutual perturbations make no longer possible to use classical techniques of orbit determination, they are a new source of information. The amplitudes and periods of these perturbations may be accurately calculated and, when big enough to be observed, serve to confirm (or not) the reality of the planets whose existence was assumed. In addition, the amplitude of these perturbations are directly proportional to the planet masses and, thus, the fit of the observations to a N-body model may allow us to determine the masses of the planets without the $\sin i$–indetermination characteristic of binary systems. The first system studied with these techniques was Gliese 876 for which (Laughlin & Chambers 2001) determined a mass factor (inverse of $\sin i$) in the 1.25–2.0 range.

3. RESONANCE

One noteworthy point in Table 1 is the great quantity of planet pairs in orbits with nearly commensurable periods. The ratio of the periods of the two Earth-like pulsar planets is nearly 3/2; that of the planets of HD 83443 is nearly 10/1; those of the planets of Gliese 876 and HD 82943 are close to 2/1 and that of 47 UMa planets is nearly 5/2. In the case of the Gliese 876 planets, later studies have shown a perfect resonance. The mean longitudes λ_1, λ_2 and the longitudes of the periastra ϖ_1, ϖ_2 are such that the composite angles $2\lambda_2 - \lambda_1 - \varpi_1$, $2\lambda_2 - \lambda_1 - \varpi_2$ and $\varpi_2 - \varpi_1$ are almost constants. The two planets move in orbits whose semi-major axes remain almost aligned, with the two periastra on the same side. The orbital period of the inner planet is not exactly twice the orbital period of the outer one; but the difference between the actual periods ratio and the fraction 2/1 is compensated by the retrograde motion of the periastra of $0^\circ.116$/day. It allows the two planets to pass, almost simultaneously, by the periastra of their orbits, at each 61 days.

This abundance of resonances is not exclusive of the new planets. Many commensurabilities of periods are observed between planetary satellites in our planetary system: for instance, we know resonances amongst the three inner Galilean satellites, and on several Saturn's satellite pairs: Enceladus-Dione, Mimas-Tethys, Janus-Epimetheus and Titan-Hyperion. In fact, we know that in presence of dissipative perturbation, an orbit evolves increasing or decreasing its dimensions and, during this evolution, two orbits in a system may go through a situation in which their periods are commensurable. If this evolution is slow enough, the system may be captured into the resonance. In the case of the planetary satellites of the Solar System, the dissipative perturbations due to tidal interactions with the central planet give rise to tiny secular variations in the semi-major axis and, in addition, affect the eccentricities circularizing the orbits. The resonant systems formed in this way are strongly stable. However, the capture into a resonance and the continued slow variation of the periods strongly excites the eccentricities of the two bodies and is, thus, also a source of instability: while the dissipation is acting, the orbits become close to a symmetrical situation, as that of the planets of Gliese 876, but the dissipation creates small delays with respect to an exactly symmetric stationary configuration and these delays give rise to torques that strongly excite the eccentricities. When the dissipative perturbation affects only the periods, the orbits may become so eccentric that the two bodies may have close approaches and the system is dynamically disrupted. The high eccentricity of many exoplanets is certainly the result of an excitation of this kind. Thus, the dissipative perturbation that brought the system to the present situation should not have affected only the periods, but also damped the eccentricities.

In the case of the planets of the star Gliese 876, the dissipative perturbation responsible for the capture into the resonance may have been the interaction of the planets with the disk of matter from which they were formed. When two big planets are formed in a disk, in orbits that are relatively close, the space between them is immediately emptied by the gravitational action of the planets. The torques provoked by the disk on the planets come from only one side and are not compensated. Consequently, the outer planet migrates inward. If enough material is remaining between the star and the orbit of the inner planet, it will migrate outward. Several simulations were done by (Lee & Peale 2001) with models where the semi-major axes are forced to vary with a rate of $5\times10^{-5}\mathrm{yr}^{-1}$ while the eccentricities damping was assumed to occur at various levels. In all simulations, when the ratio of the two semi-major axes reaches the value 0.62, the 2/1 period commensurability is reached and the system is captured into the resonance. As the energy loss continues due to the model conditions, the period variation of the planets does not cease. The resonant interaction between the two planets allows an energy transfer between the planets in such way that the whole system is kept captured into the resonance, even when the model forces the semi-major axis variation in only one of them. In absence of eccentricity damping, the eccentricities may increase beyond any limits. In presence of eccentricity damping, however, they increase up to reach a limit value that becomes almost constant. The intensity of the eccentricity damping may be adjusted to give limit values equal to those currently observed.

4. CHAOS

The techniques used to study the chaos and stability of the planets of our Solar System may be extended to the study of the newly discovered systems.

The techniques developed by Michtchenko & Ferraz-Mello (2001) were used to map the chaotic regions in the neighborhood of the planets of PSR B 1257+12 (see Figure 1). The given figure shows the neighborhood of the third pulsar planet. To obtain it, the elements of the two inner planets were kept fixed, while the semi-major axis and eccentricity of the third planet were arbitrarily taken on a grid of values around the actual one (shown by a cross). The figure shows that the actual system lies in a very stable region. The dark regions where strong chaos and instability are observed are far from the actual pulsar planets. The two outer planets are close to the 3/2 period resonance. This proximity is responsible for a large-amplitude mutual perturbation, with period 2066 days, actually observed in the time series formed with the observations of the pulsar (Konacki et al. 1999). However, the time span of the existing observations is only ~4 years and it is hoped that this result be confirmed by new observations. The amplitude of the perturbation indicates a mass factor less than 1.15 (Wolszczan 1997). Simulations done by (Quintana et al. 2001) show that with a mass factor 1.4, the system becomes unstable and unable to survive more than a few hundred thousand years.

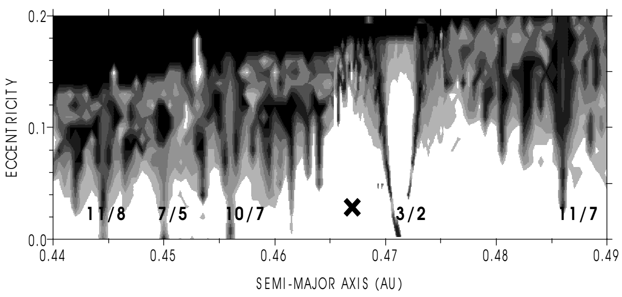

Fig. 1. Regular (white) and chaotic (grey to black) regions in the neighborhood of Pulsar planet C (×). The positions of 3/2 and other resonances are indicated

The frequency map analysis was used by (Robutel & Laskar 2000) to map the neighborhood of the planets of υ And. Their results show that with a mass factor larger than 3, these planets would be immersed in the chaotic region. They have also shown that, in the neighborhood of the planets of υ And, a stable Earth size planet could only exist in nearly circular orbits beyond 8–9 AU from the star.

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